Dispersion and Confinement Loss Analysis of Nonlinear Square Lattice Photonic Crystal Fibers Employing Air Holes in the Cladding Region

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Abstract: ***The three main properties of PCF, namely confinement loss, dispersion, and effective area are numerically investigated using the finite element method for the four patterns of square lattice fiber. The fibers have identical structures with five air hole rings, yet the dimension and shape of the air holes of the first ring (ring near the core) differ in their structures. Circular and elliptical air holes have been used in these patterns. It is found that the low chromatic dispersion, low loss and small effective area can be obtained in the wavelength range of 1340 to 1680 nm. The nonlinear coefficient is approximately 11˜15W^{-1}km-^{1} at 1550nm wavelength.***

Keywords: chromatic dispersion, confinement loss, finite element method, nonlinear coefficient.

1. Introduction

High dispersion in conventional single mode fibers leads to partial loss of data in long distances of data transmission. Thus, researchers began to devise new optical transmission media with zero dispersion and uniform response in different wavelength channels. In WDM communication systems, it s essential to maintain a uniform response in the different wavelength channels, which requires that the transmission line approach the ideal state of ultra-flattened dispersion and ultra-low loss [1].

In the recent years, photonic crystal fibers (PCFs) have attracted much interest among researchers. Photonic crystal fiber (PCF) is formed from a strand of silica glass with an array of microscopic air channels running along its length [2].They are also referred as air-silica, holey or micro-structured fibers. The PCFs can be classified according to their core, which is air or silica. In solid-core or index guiding fibers, the index difference between the core and cladding is a positive value; hence the light is guided along the fiber through total internal reflection (TIR) mechanism.

Reducing dispersion and confinement loss are of the main concerns in designing PCFs. Several designs for the PCFs have been proposed to achieve the nearly zero ultra-flattened chromatic dispersion properties and low confinement loss. Hansen proposed a hybrid-core photonic crystal fiber with three-fold symmetry, in which dispersion and its slope is well restrained, however, the confinement loss was shown to be about 10^{-3}[3]. In recent years, better results have been observed [3]-[11] as a result of different approaches adopted, e.g. modifying the form of the hole into ellipse [8], Gradually increasing the diameter of the hole from inner ring to the outer [4], selectively filling the PCF with liquids [6], application of double cladding [10], etc.

Propagation characteristics of the photonic crystal fibers with square-lattice structures have been recently studied and reported [12]-[16]. Dispersion properties and effective modal area of PCFs with triangular and square-lattice structures were compared [17]-[18]. In 2009, a square-lattice PCF structure with ultra-flattened dispersion was designed, in which dispersion demonstrated slight variations of 0 ± 0.06 ps/(km·nm) within wavelength range of 1.375 to 1.605 μm and the confinement loss was below 0.1 dB/km in the same range [19].

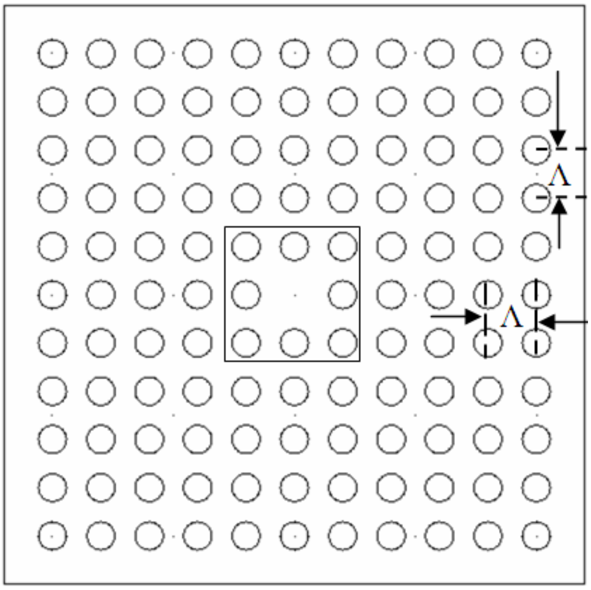
In this paper, four patterns for square-lattice PCFs with 5 air-hole rings are investigated. The four patterns are proposed by optimizing the design parameters of the air holes of first ring. For the purpose of analyzing and simulating the propagation characteristics of the proposed photonic crystal fiber, finite-element method (FEM) method with the isotropic perfectly matched layers (PML) boundary conditions has been employed.

2. Design Parameters

Figure 1 shows the structure of the proposed index guiding SPCFs with five rings. The fiber is composed of circular air holes in the cladding region arranged in a square array, where Λ is the centre to center spacing between the air holes, d is the air hole diameter of the circular holes , d/Λ is the normalized diameter of the air holes in the cladding and $2a=2\Lambda-d$ is the core length. For elliptical air holes, the major axis is defined as a, the minor axis is defined as b. The ellipticity is defined as the ratio of major axis and minor axis i.e, a/b. The wafer is chosen of pure silica with refractive index 1.45 and the refractive index of air holes is 1.

For configuration-I, the all air holes in the cladding region are circular. The diameter of the circular holes d=1.158μm.

For configuration-II, the air holes of the first ring near the Cores are elliptical. The remaining holes in the cladding region are circular. The diameter of the circular holes d=1.158μm.For the elliptical holes, the parameters are, the major axis, a = 1.4 μm, the minor axis, b = .838μm.



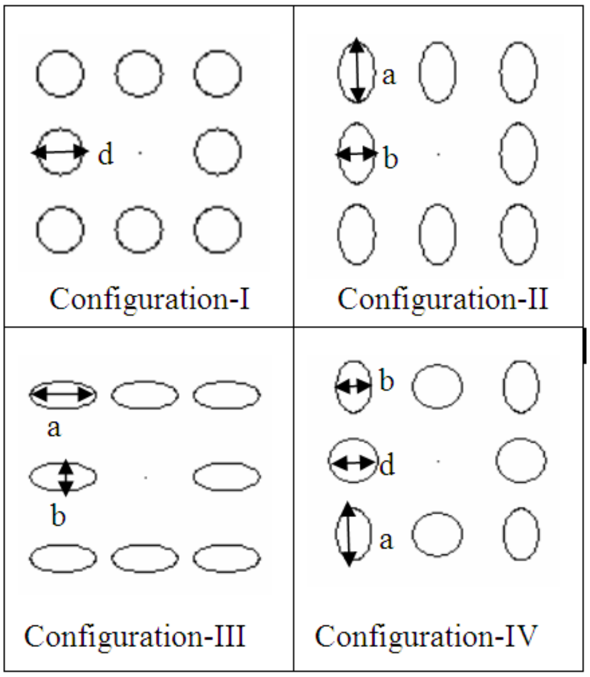


Figure 1. Cross-section of four configurations of proposed PCF structures

For configuration-III, the air holes of the first ring near the core are elliptical. The remaining holes in the cladding region are circular. The diameter of the circular holes, d=1.158µm.For the elliptical holes, the parameters are, the major axis, a = 1.6µm , the minor axis, b = .68 µm.

For configuration-IV, the first ring is composed of both circular and elliptical holes. The remaining holes in the cladding region are circular. The diameter of the circular holes, d=1.158µm.For the elliptical holes, the parameters are, the major axis, a = 1.4 µm, the minor axis, b = .838µm.

For all the configurations (I-IV), the centre to center spacing between the air holes, Λ=2µm.

3. Equations for Calculation

Effective mode index of a guided mode for a given wavelength is obtained by solving an eigenvalue problem drawn from the Maxwell equations using the Finite element method. Effective mode index, n_{eff} can be obtained as $n_{eff} = \frac{\beta}{k_0}$.Here, β is the propagation constant and $k_0 = \frac{2\pi}{\lambda}$ is the free space number. The effective mode index has both real and imaginary parts.

Once the modal effective indices n_{eff} is obtained, the chromatic dispersion parameter D(λ)[20], confinement loss parameter L_c [20],effective area A_{eff} [20], the nonlinear co-efficient γ[21]G can be given by

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d\lambda^2} \quad (1)$$

$$L_c = 8.868 \times k_0 \times \mathrm{Im}[n_{eff}] \quad (2)$$

$$A_{eff} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2\,dxdy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^4\,dxdy} \quad (3)$$

$$\gamma = \frac{\omega}{c}\left(\frac{n_2}{A_{eff}}\right) = \frac{2\pi}{\lambda}\left(\frac{n_2}{A_{eff}}\right) \quad (4)$$

where $\mathrm{Re}[n_{eff}]$ is the real part of n_{eff}, λ is the operating wavelength, c is the speed of light in vacuum, n_2 is the nonlinear refractive index of silica (~$2.23\mathrm{X}10^{-20}$ m^2/W) and E is the electric field derived by solving Maxwell's equations. Here, $\mathrm{Im}[n_{eff}]$ is the imaginary part of n_{eff}. The material dispersion is given by Sellmeier equation which is directly included in the equation. Therefore, $D(\lambda)$ in (1) corresponds to the total dispersion of the PCFs. The total dispersion is sum of the material dispersion and the waveguide dispersion.

4. Simulation Results

Figure 2 shows the chromatic dispersion, the confinement loss and the effective area as a function of wavelength for the five ring PCFs shown in Fig. 1.The simulation has been done for the wavelength range of 1340 to 1680nm.

For Configuration-I, the positive dispersion and the negative dispersion slope at 1550nm wavelength are 0.4941ps/ (nm-km) and -0.02772ps/(nm^2-km) respectively. At 1550nm wavelength, the effective area is 7.9179µm^2 wavelength and the non-linear co-efficient is 11.42$W^{-1}km^{-1}$. The confinement loss is less than 10^{-2}dB/km in the wavelength range of 1340 to 1550 nm. The zero dispersion can be obtained at λ= 1565µm.

For Configuration-II, the negative dispersion and the negative dispersion slope at 1550nm wavelength are

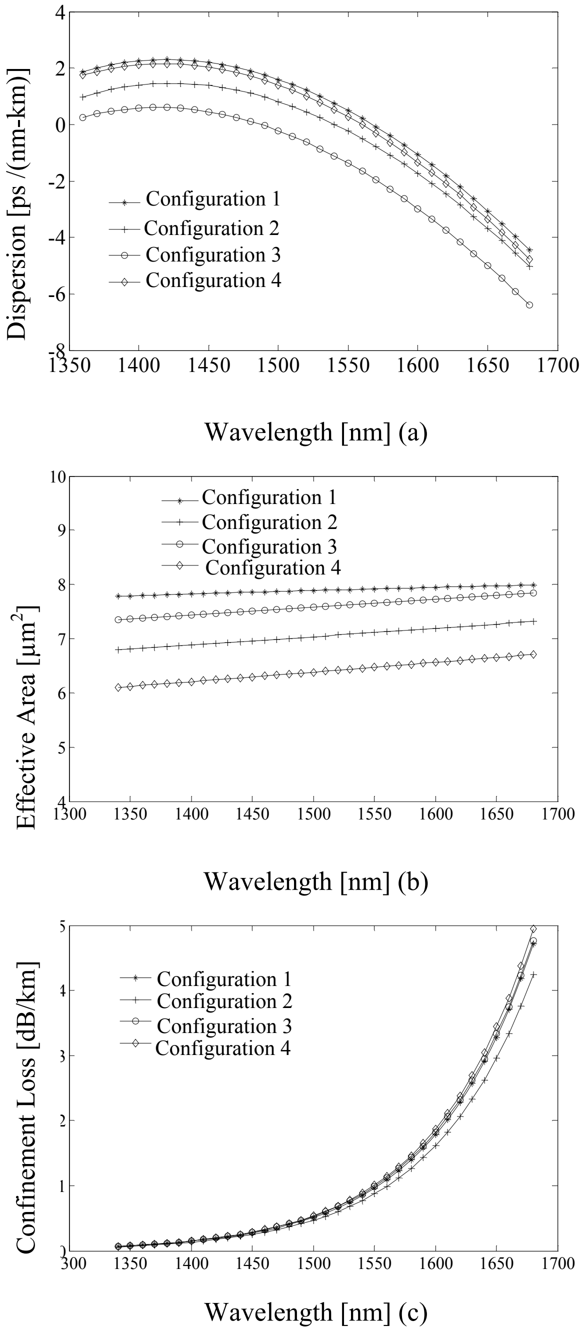


Figure 2. (a) Chromatic dispersion curve,(b)effective area, and (c) confinement loss as a functions of wavelength for proposed SPCF at the condition of Λ=2.0μm

-0.2398ps/ (nm-km) and -0.02666ps/(nm^2-km) respectively. At 1550nm wavelength, the effective area is 7.1121μm^2 and the non-linear co-efficient is 12.71W^{-1}km^{-1}. The confinement loss is less than 10^{-2}dB/km in the wavelength range of 1340 to 1560 nm. The result shows that zero dispersion can be achieved at λ= 1540μm.

For Configuration-III, the negative dispersion and the negative dispersion slope at 1550nm wavelength are -1.3774ps/ (nm-km) and -0.02871ps/(nm^2-km) respectively. At 1550nm wavelength, the effective area is 7.6492μm^2 and the non-linear co-efficient is 11.81W^{-1}km^{-1}. The confinement loss is less than 10^{-2}dB/km in the wavelength range of 1340 to 1550 nm. The result reveals that zero dispersion can be achieved at λ=1490 μm.

For Configuration-IV, the positive dispersion and the negative dispersion slope at 1550nm wavelength are 0.2668ps/ (nm-km) and -0.02499ps/(nm^2-km) respectively. At 1550nm wavelength, the effective area is 6.4711μm^2 and the non-linear co-efficient is 13.96W^{-1}km^{-1}. The confinement loss is less than 10^{-2}dB/km in the wavelength range of 1340 to 1550 nm. The zero dispersion can be obtained at λ=1560 μm.

The comparison of the numerical results shown in Fig .2 are summarized in Table 1.The table also includes the values of non-linear co-efficient calculated at λ=1550nm for the four patterns.

Table 1: Different Properties of proposed PCFs

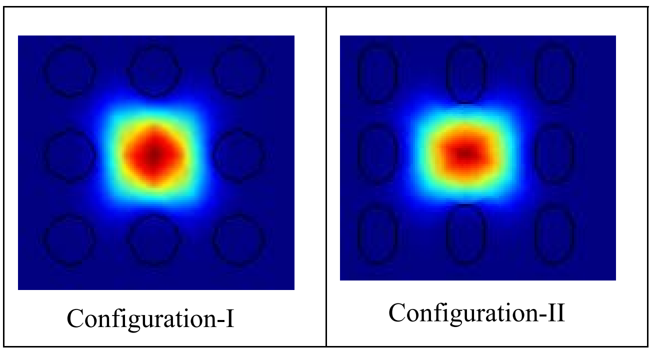
λ=1150 nm	Configuration-I	Configuration-II	Configuration-III	Configuration-IV
Dispersion(ps/nm-km)	0.4941	-0.2398	-1.3774	0.2668
Effective Area(μm)	7.9179	7.1121	7.6492	6.4711
Confinement Loss(dB/km)	0.0096	0.0088	0.0099	0.0101
Nonlinear Coefficient($W^{-1}km^{-1}$)	11.42	12.71	11.81	13.96

The measured zero dispersion wavelengths for the four configurations are summarized in Table 2.

Table 2: Zero dispersion wavelengths of proposed configurations

Zero Dispersion Wavelength(nm)	Configuration-I	Configuration-II	Configuration-III	Configuration-IV
	1565	1540	1490	1560

Mode profile of the PCFs at 1550nm is shown in Fig. 3.It is found that the mode profiles are almost square and the peak value of the intensity lie at the center of the core. It means that the proposed PCFs can confine the electric field strongly. The numerical simulations show that the proposed PCFs do not support higher order modes in the wavelength of 1340nm t0 1680nm.Therefore the proposed PCFs can operate as single mode fibers in the telecommunication window.



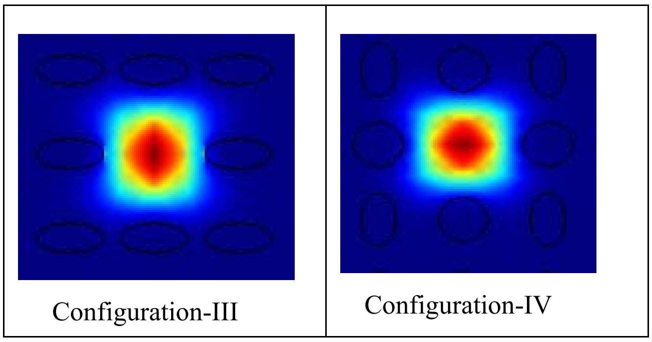


Figure 3. Mode profile of four configurations (I-IV) of proposed SPCF at 1550nm wavelength

5. Conclusion

Four configurations of square lattice fiber employing air holes in the cladding region have been numerically investigated. At 1550nm, the magnitudes of lowest effective area and largest nonlinear coefficient are 6.4711μm^2 and 14.78$W^{-1}km^{-1}$ respectively and these values are obtained for Configuration-IV. The lowest positive dispersion is also obtained for this configuration and the value is 0.2668ps/(nm-km). Zero dispersion wavelengths for this configuration is achieved at 1560nm wavelength. For all four configurations, the confinement loss is less than 10^{-2}dB/km at the wavelength range of 1340 to 1550 nm. The nonlinear coefficient is approximately 11-14$W^{-1}km^{-1}$ at 1550nm wavelength. Due to these properties, proposed PCFs can be suitable for optical switching, soliton formation, and wavelength conversion, broadband amplification, DWDM etc.

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